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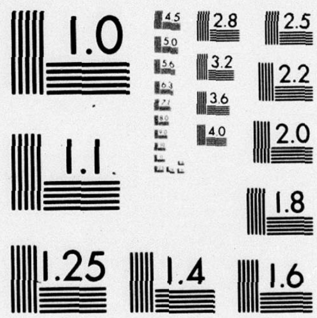

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SOLID-STATE LASER WAVELENGTH IDENTIFICATION USING A REFERENCE ABSORBER

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June 1977

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A Fabry-Perot etalon is used to identify the relative wavelengths of individual spikes in the long-pulse output of a homogeneously broadened, solid-state laser. This identification is accomplished by positioning one side of a low finesse etalon bandpass such that it is coincident with the laser output. Different wavelength spikes experience different attenuations on passing through the etalon, thus enabling a relative wavelength determination from the etalon transmission value. The etalon is incorporated into a real-time minicomputer

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20. Abstract (cont)

controlled measuring system capable of storing, analyzing, and displaying various parameters encountered in laser interaction studies. By utilizing the narrow spectral width of individual laser spikes (< 0.0001 nm) and the large number of different wavelength spikes available in a single long pulse (tens to hundreds), many high-resolution spectral data points can be obtained within the period of one laser shot (< 4 ms). Experimental results of the transmission of erbium:YAG laser radiation in a methane-enriched atmosphere are shown to illustrate one use for the system.

This technique provides an accurate means of studying the interaction and propagation nature of certain solid-state lasers used by the Army. The causes of degradation in Army laser systems may be studied with a higher degree of precision, thereby allowing possible minimization or elimination of any such effects.

CONTENTS

INTRODUCTION

The Army has a continuing need for lasers in field systems such as range finders and target designators. Since gases and particulates in the atmosphere will affect the performance of any laser system, their effects must be well understood before a total system analysis can be completed. For a complete understanding of laser propagation characteristics, the spectral nature of the laser energy must be known in addition to the absorption properties of the atmosphere. Previous atmospheric propagation studies for various solid-state lasers were hindered by limited spectrometer resolution [1]. To investigate the interaction of laser energy with atmospheric gas absorption lines, a new high-resolution measuring technique was developed. The system allows relative wavelength identification of the individual laser spikes in a long-pulse laser output.

The emission from a long-pulse solid-state laser consists of a series of spikes. If the laser is homogeneously broadened, or nearly so, and care is taken in the alignment [2], the spikes will consist of only one longitudinal mode. These spikes can be used for high-resolution gas absorption studies if a method of wavelength identification can be found, since the spikes do not occur in any predictable way within the gain envelope of the laser and vary in spectral position from shot to shot. Methods have been developed to identify wavelengths by using spectrometers [3]; however, the ultimate spectrometer resolution available (about 10^{-2} nm) is far from sufficient to allow accurate sorting of single mode laser spikes for high-resolution studies.

The new idea is simply to measure the transmission of a laser spike through a known absorber in which the absorption is a monotonic function of wavelength. The relative wavelength of the laser spike can be obtained from this measurement. One method of measuring is by positioning one side of a low finesse Fabry-Perot etalon bandpass such that it is coincident with the laser output spectrum. Different wavelength laser spikes experience different attenuations on passing through the etalon. Thus, a relative wavelength tag can be associated with the etalon transmission value of a given laser spike.

An investigation to study the atmospheric propagation characteristics of the erbium:ytterbium-aluminum-garnet (YAG) laser energy was the impetus for the development of the above technique. Carbon dioxide and water vapor are the principal infrared absorbers [4], but neither has a major absorption band in the spectral region of the 1.645μm laser emission. However, there are several minor absorption bands and many weak lines [5] which impart a considerable amount of spectral structure to this region. A close wavelength coincidence had been previously discovered [1] between the erbium:YAG laser radiation and the R(6) line in the $2\nu_3$ methane band at 1645.1 nm. The potential application of this coincidence to the remote sensing of atmospheric methane has been discussed elsewhere [6]. Theory predicts that this overtone line is composed of six fine structure compacts [7,8], two groups of three separated by 0.22 nm [8,9]. The relative spectral positions of the methane absorption line, erbium:YAG laser emission, and etalon transmission are shown in Fig. 1. The new measuring technique was developed in an attempt to resolve this absorption interaction.

The experimental arrangement, including properties of the laser, etalon, and data acquisition system, and experimental results are presented in the following sections.

EXPERIMENTAL ARRANGEMENT

The experimental arrangement is illustrated in Fig. 2. The optical system consists of: (1) a reference amplitude detector, (2) the absorption cell and output detector, (3) the spike wavelength identifying mechanism (Fabry-Perot etalon and detector), and (4) a wavelength region identifying instrument (5-m spectrometer). The data acquisition system consists of three analog-to-digital converters (ADC), an ADC data identifier (ADI), an interactive terminal, and an HP 2100A minicomputer.

Laser Parameters

The laser consists of a 6 mm diameter by 75 mm long YAG rod doped with 0.4% erbium and sensitized with 5% ytterbium [10,11]. A linear xenon flash lamp is used in a close-wrap intersecting circle cavity which is cooled by flowing nitrogen gas. The laser interferometer consists of a plane parallel cavity with a 99.9% reflectivity back mirror and a 95% reflectivity output mirror 26.5 cm apart (the rod ends being antireflection coated). The laser cavity and the optical system are aligned by using a He-Ne laser beam coincident with the erbium laser beam. A nicol prism is placed at the laser output to obtain a vertically polarized beam. With this configuration the threshold is approximately 200 joules. The nominal output slightly above threshold is 10-30 millijoules per pulse in the long pulse mode of operation. Laser emission is centered at 1644.9 nm with a spectral bandwidth of approximately 0.6 nm.

In this laser the initial depopulation of the excited state is so large that lasing ceases until the population inversion can be restored by continued pumping--at which point the process repeats itself (Fig. 3). This procedure results in a long pulse mode output consisting of a 0.5 to 4 millisecond train of single-mode (frequency) spikes. Near threshold the spikes occur singly with respect to time. This behavior was enhanced by placing two 1 mm diameter apertures in the laser cavity and thereby reducing the usable gain medium volume. The above temporal behavior is a necessary condition for the data acquisition system to be able to analyze the individual spike peak intensities. The data analysis system automatically rejects spikes in very rapid succession and any spike overlapping due to detector decay time (Fig. 3).

Since the measuring system uses the absorption values for individual laser spikes, the system's resolving power is inherently a function of the spectral width of each spike. The erbium laser approaches being homogeneously broadened. In a homogeneously broadened system, there may be several cavity modes which have gains above threshold (Fig. 4a) at the start of laser action. As energy builds up at these frequencies, the modes compete with each other for the inverted population, and the total gain drops (gain saturation) [12], until only one mode is left above the threshold gain (Fig. 4b). The output thus ideally consists of a single frequency corresponding to the mode with the highest initial gain. If only one longitudinal mode was to oscillate, the bandwidth of a single spike should be extremely narrow (< 0.0001 nm, based on theoretical laser interferometer finesse).

Even though the erbium laser is not an ideal homogenously broadened system, operation with single frequency spikes may be enhanced by aligning the cavity mirrors parallel to the ends of the laser rod [2]. This provides an intracavity mode-selecting resonator with a high effective finesse, since it contains the laser's gain medium. An upper limit for the spectral width of an individual spike was experimentally set at less than 0.01 nm [13] by using a 5 m grating spectrometer with a linear fiber optic bundle in its output plane (the maximum spectrometer resolution was 10^{-2} nm).

Wavelength Identifier

A Fabry-Perot etalon with plane parallel mirrors is used to identify the wavelength of the individual spikes with respect to each other. An etalon bandpass is positioned as in Fig. 5 by changing mirror spacing. For this positioning, shorter wavelength spikes (λ_0) give rise to lower etalon transmission values (T_0) than longer wavelength spikes (λn, Tn). Therefore, by plotting the gaseous transmission values for the spikes versus etalon transmission values, a profile of the absorption line can be obtained.

By using a computer model [14] of the transmission characteristics of the etalon, the necessary mirror reflectivities and spacing were obtained for the wavelength region of interest. The objective was to obtain a bandpass which was linear over the desired spectral range (absorption line) while possessing the maximum dynamic range of transmission. For this case, 40% reflectivity mirrors with approximately 0.5 mm spacing gave these desired characteristics. The etalon has a finesse of 3.31, with a free spectral range of 2.7 nm and bandpass full-width at half maximum of 0.82 nm. For studying specific sections of a highly structured absorption line, a narrower bandpass with an increased transmission versus wavelength slope might be used.

The measuring system's resolving ability is highly dependent on the resolution and stability of the etalon. About 0.1 nm of the etalon bandpass (in the linear region) is used in the measurement. The detector signals obtained from the laser spikes in this spectral region can be made to range over a 10-V region which in turn is digitized by using 2048 channel resolution. Thus, a theoretical spectral resolution of about 5×10^{-5} nm is obtainable. This is on the order of the width of the single mode laser spikes. A 3 mm diameter aperture is used to limit the etalon mirror surface area used so that the spikes encounter minimal differences in mirror reflectivity and spacing; this procedure helps to ensure a linear and uniform bandpass for all spikes.

The etalon is Invar housed with piezoelectric electromicrometers for both mirror alignment and spacing. The construction minimizes thermal and mechanical stability problems [15]. Thermal shifts were seen to be minimal due to the Invar construction and thermal expansive compensation (one component expands in a direction opposite to another). A 61 nm change of the 0.5 mm etalon mirror spacing will cause a theoretical change of 20% in the transmission of a particular wavelength through the etalon. This shift would not be of any consequence if all the necessary data points could be accumulated within one long pulse since the mechanical vibration noise has a period longer than the 4 ms laser shot (the system is mounted on a massive optical table). For the methane absorption line under consideration, the laser is just partially coincident, so only a few of the spikes in a long pulse fall on the line. Therefore, more than one shot is needed to obtain a sufficient amount of data. Any etalon mirror spacing shift between laser shots would result in a corresponding offset in wavelength positions between the different sets of data.

Other Systems

A 5 m Fastie spectrometer is used to select portions of the laser spectral output for analysis (Fig. 5). The signal from a detector behind the spectrometer slit (Fig. 2) acts as a "gate" for the data acquisition system, allowing only those laser spikes with wavelengths within the spectrometer slit to be analyzed. This is used to observe etalon transmission values for positioning the bandpass and to analyze the absorption characteristics of specific wavelength regions. The computer/ADI sorts data in up to four separate memory sections depending on the coincident "gate" signal from different spectral positions in the output plane of the spectrometer [16]. This allows real-time system calibration to compensate for long-term changes.

Detector arrangement is shown in Fig. 6. Originally some problems were encountered with spikes hitting different parts of the active area of the photodiode and causing erratic results. A membrane filter was incorporated into the arrangement to diffuse the laser spike energy such that it is averaged over the entire active area.

The absorption cell (Fig. 2) is constructed from 7.5 cm diameter Pyrex tubing 0.62 m long with antireflection coated entrance and exit windows. The absorption path consists of a single pass through 100 torr of CH_4 broadened with 560 torr of N_2. The cell temperature was maintained at 22°C and the pressures were monitored by a capacitance nanometer.

Data Analysis System

A minicomputer controlled pulse-height analyzer is used to store, analyze, and display the information from the three simultaneous signals: (1) reference (cell input), (2) absorption (cell output), and (3) etalon (etalon output). This basic data acquisition and analysis system has been described in detail elsewhere [17]. The peak amplitude of the signals from the reference, absorptions, and etalon detectors are sampled and digitized into corresponding 14-bit digital words (up to 8192 channels) by the three ADCs. These words are held in a buffer until the minicomputer signals that it is ready for data transfer. An additional two bits are added to the etalon ADC word via the ADI unit. This enables data to be routed into up to four different memory locations when some identifying coincidence signal is present on one of the four ADI inputs at the same time data is present. The three ADCs are run in coincidence mode, which means that they can only accept data when a coincidence pulse is present (e.g., spectrometer gating), thereby insuring correlation between the three signals for an individual spike.

Data transfer to memory is accomplished through the use of two direct-memory access (DMA) channels for the reference and absorption digital words and one microprogrammed channel for the etalon. To maintain the correlation between the three ADCs, the reference and absorption ADCs are hardwire "slaved" to the etalon ADC.

The three digital heights for a spike are transferred to the minicomputer only when the etalon ADC signals that it has data to transfer.. Also, no ADC can accept new data until the microprogrammed (etalon) channel has finished data transfer. This is necessary since the DMA channels operate basically independent from the minicomputer's central processor unit (CPU), while the microprogramming requires seven CPU cycles or 6.86μs to transfer data. This and the minimum time between successive laser spikes determines the minimum usable ADC pulse height resolution. Once the three simultaneous ADC words for all spikes in a long pulse are in memory, computations can be initiated.

The ratio of the absorption cell signal to reference signal allows the transmittance of each spike through the gas to be calculated. The etalon signal to reference signal is the etalon transmittance and is used to. identify laser spike wavelengths with respect to each other. Plotting the absorption cell transmission values versus the etalon transmission gives a visual display of any absorption feature. Scale magnification is possible with the computer system, allowing closer scrutiny of highly structured sections. The data from several different laser shots can be plotted together or separately.

With this system, approximately 40 data points can be obtained within less than 4 ms, the time duration of one long-pulse laser shot. This insures minimal influence on system calibration by time-varying problems.

EXPERIMENTAL RESULTS AND COMMENTS

Positioning of the etalon bandpass is especially critical. To achieve correct positioning the spectrometer is used to "gate" the system for a specific wavelength range, while the etalon spacing crystal is scanned. A typical plot of this type of data is illustrated in Fig. 7 for spikes not coincident with the absorption line. As the etalon is scanned, the transmission range for a set wavelength increment (spectrometer slit width) changes. On the peak of the bandpass (Fig. 7a), dynamic transmission range is minimal while transmission is greatest. As the side of the bandpass is scanned, the total range of etalon transmission values increases and maximum dynamic range position is obtained (Fig. 7b). This is the desired position. Further scanning positions the wing region of the etalon bandpass on top of the wavelength range, again giving minimal dynamic range, but this time with minimum transmission.

Figure 8 is a sequence of data taken with different spectrometer slit positions after the etalon bandpass has been positioned on the absorption line as in Fig. 1. In Fig. 8a the spectrometer slit is located off of the absorption line. As the slit is moved, more of the absorption line can be seen (Figs. 8b and 8c). The total line could not be scanned since the erbium:YAG laser output did not span the entire absorption line. Other coincident absorption lines may be investigated in the future.

Use of this system is not limited to obtaining spectral profiles of coincident gas absorption lines. The system may be used in any long-pulse laser interaction study. Three ADCs were utilized in this system, but many more microprogrammed transfer channels may be added with a small increase in data acquisition time (10μs per ADC). The main resolution limitations in this system are the etalon stability and the timing requirements which determine the maximum usable number of ADC pulse height channels.

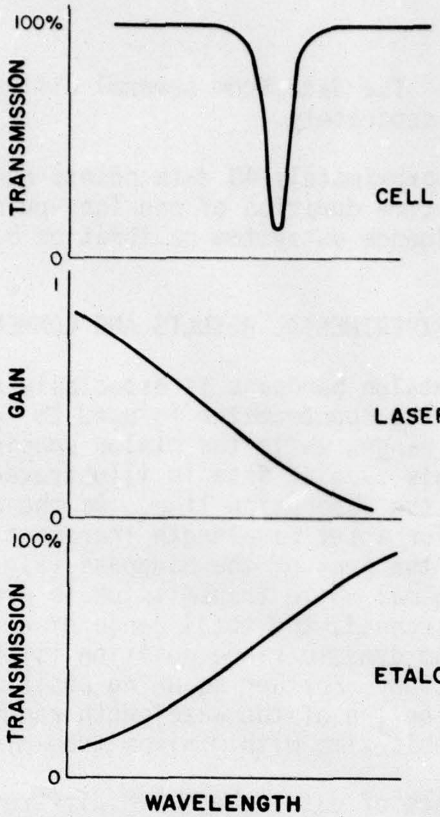

Figure 1. Relative wavelength positions of absorption cell transmission of R(6) $2\nu_3$ line of $^{12}CH_4$, YAG:Er, Yb laser output at 22°C, and typical etalon bandpass positioning.

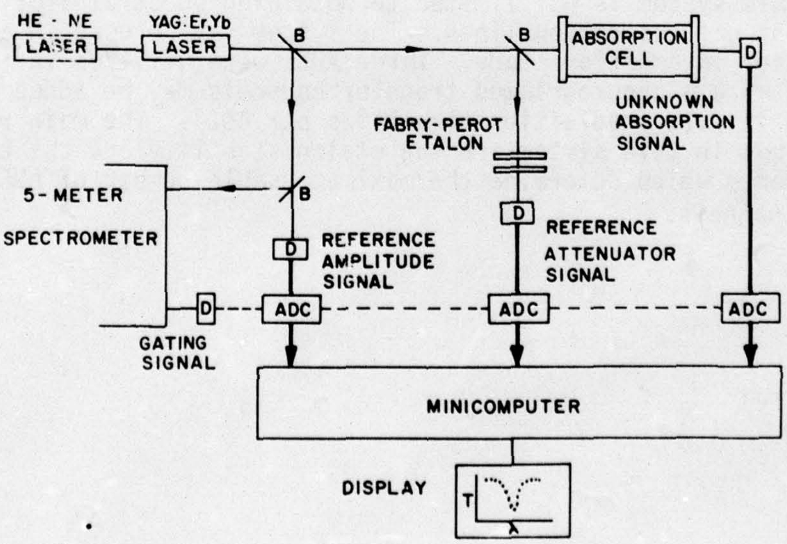

Figure 2. Diagram of the experimental arrangement for observing laser energy interaction with gases. The darker lines are electrical signals. B: beamsplitter, D: detector.

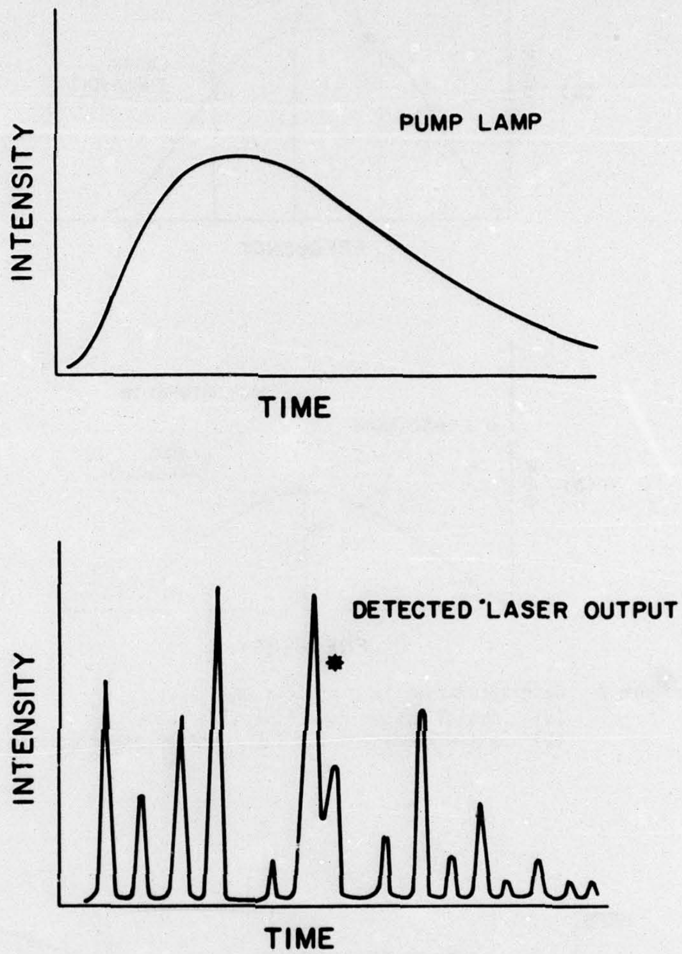

Figure 3. Operation of laser in long pulse mode. (*) denotes spike pulse overlapping due to detector decay time.

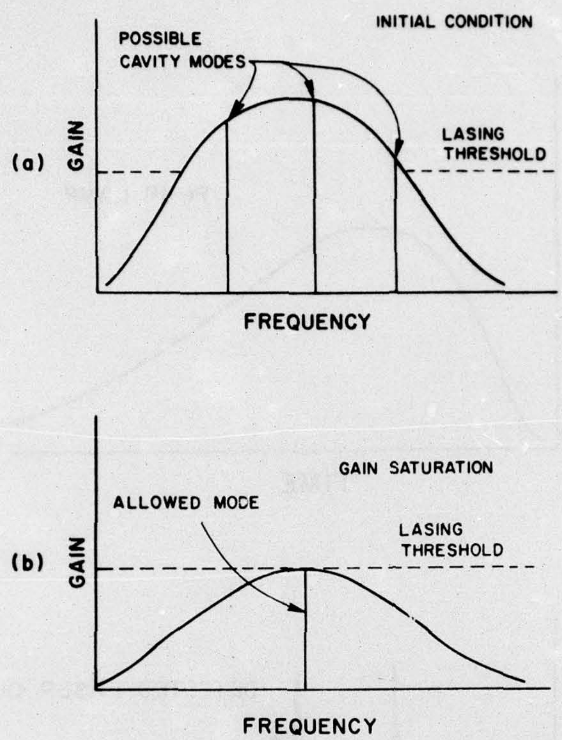

Figure 4. Gain saturation in a solid-state laser.
(a) Initial system condition.
(b) System condition for laser action after gain saturation.

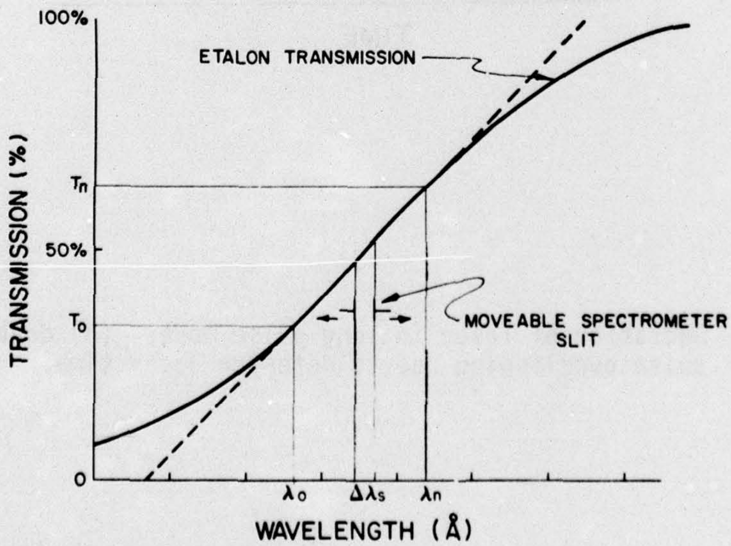

Figure 5. Etalon bandpass and possible spectrometer slit positioning.

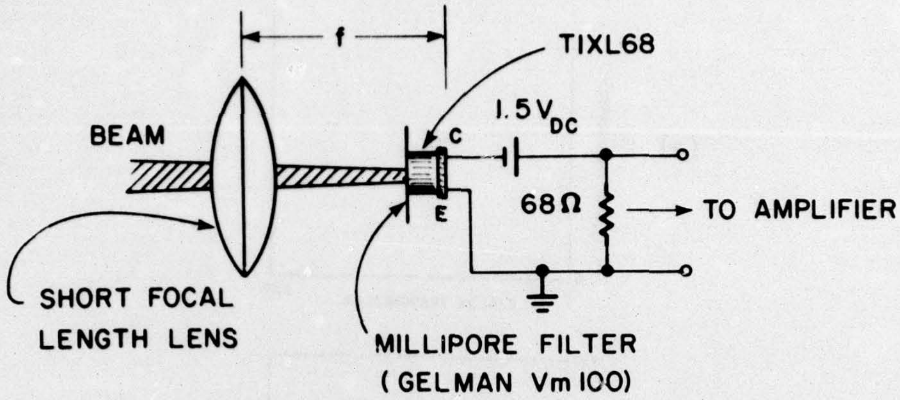

Figure 6. Detector arrangement. TIXL68 is a germanium photodiode.

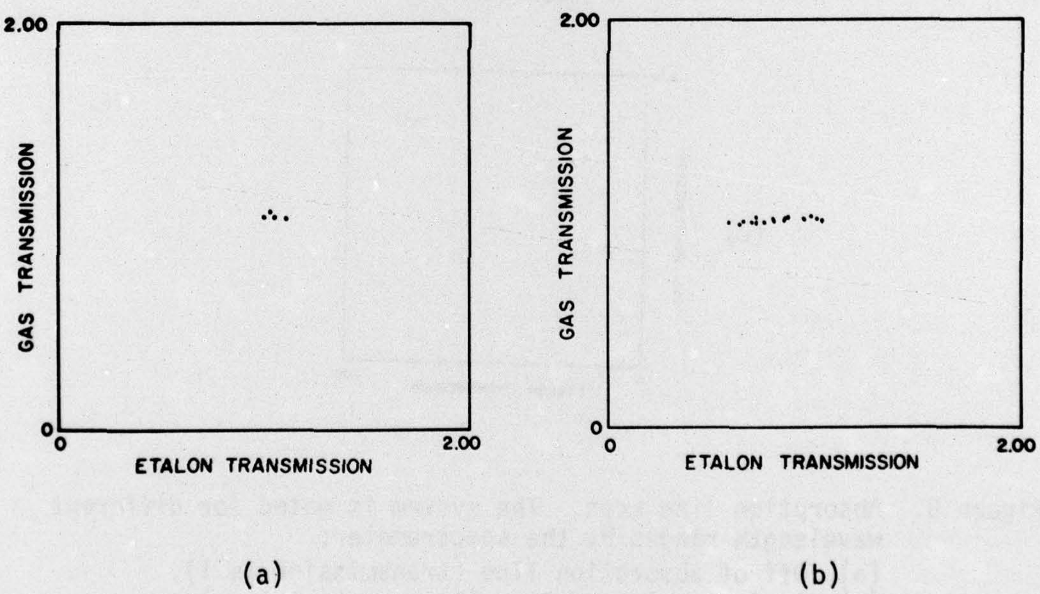

Figure 7. Etalon spacing positions. The different positions were obtained by changing the voltage on the piezoelectric spacing crystal.
(a) Peak of bandpass.
(b) Position for maximum dynamic transmission range.

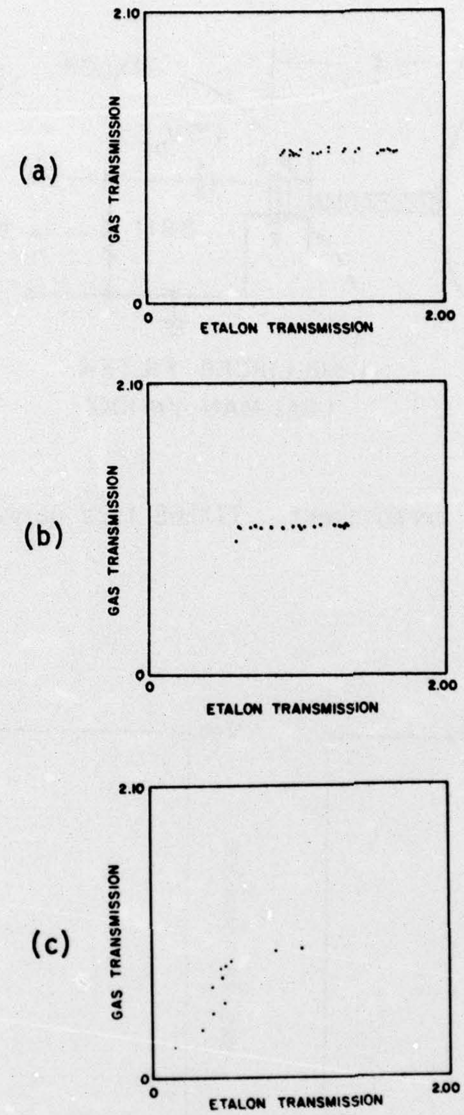

Figure 8. Absorption line scan. The system is gated for different wavelength ranges by the spectrometer:
(a) Off of absorption line (transmission is 1).
(b) A wing region of line (lower data points).
(c) Into line.

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